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Analysis of the Impact of Photovoltaic Glasses in Daylighting and Thermoenergetic Performances in an Office Room

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Abstract: Contemporary office buildings have been calling attention for intense use of glass on their façades. This way, glazed areas in such buildings may favor the access to natural light and contribute to power generation through photovoltaic systems. However, the application of STPV (Semi-Transparent Photovoltaic) may interfere with the building's energy performance and good use of daylight. So, this work aims to assess daylighting and thermoenergetic performances in an office room located in southern Brazil, with different types of STPV applied to the building's glasses. This study was carried out through computer simulation, integrating software's Rhinoceros with DIVA plugin and EnergyPlus. Results have shown that the application of STPV with proper transparency percentage provides access to daylighting and increases visual comfort for occupants, and also contributes to the building's energy balance, as it may save from 9.6% to 28% in energy. Its use, in the climatic context analyzed, has boosted energy consumption for cooling and for artificial lighting; however, photovoltaic generation was higher and thus compensated for the increase caused by the system.

Key words: Energy efficiency, STPV façades, computer simulation, lighting performance, thermoenergetic performance.

1. Introduction

In Brazil, concern with energy efficiency has increased after the petroleum crisis around 1973. This event has triggered a need to reduce energy consumption in buildings and in the last years the matter has received relevant attention globally. About 42% of Brazilian electric power is consumed in buildings, of which 16.9% are commercial ones [1]. Thus, it must be considered that buildings are relevant elements for a sustainable future. Energy consumption in buildings is directly connected to the envelopment's losses and gains of heat, which, associated with internal loads generated from occupation, use of equipment and electric lighting, which tend to overheat environments, result in an increase of consumption of air conditioning systems [2, 3]. According to Didoné [4], the projects of many commercial buildings prioritize esthetical features and end up not using the natural resources available in the best possible manner. In this aspect, daylighting, if adequately used, may have an important role in reducing energy consumption, in addition to other advantages: research [5-8] has shown preference for natural views and daylighting, as opposed to artificial lighting, positive impact on productivity and performance, and more recently, strong impact on circadian rhythms [9]. Also, the use of daylighting may reduce energy consumption due to electric lighting, however, there must be some caution with excessive daylight, for it may increase both energy consumption and visual discomfort. Considering the great offer of solar radiation all over the country, Brazil has great potential to explore solar energy through PV (photovoltaic) technologies, which can be easily integrated to buildings (BIPV—Building Integrated Photovoltaics), for they are, among the

Corresponding author: Eduardo Grala da Cunha, Dr., Professor, research fields: energy efficiency, thermal comfort, and computer simulation.

renewable energy sources available, the ones that present more possibilities of integration [10]. According to Didoné et al. [11], STPV (semi-transparent photovoltaic) systems are a good alternative to generate electric power, along with an annual reduction of consumption for cooling, as they favor the building's energy balance and transmission of daylight. In order to assess STPV systems, it is mandatory to carry out analysis on energy and daylighting together, as results reflect on each other. So, this study aims to analyze, through computer simulation, the daylighting and thermoenergetic performances of an office located in southern Brazil, applying STPV technologies into the building's façade glazed areas.

2. Theoretical Foundation

The concept of energy efficient building is linked to the reduction of consumption of electric power, which directly affects the reduction of thermal loads of this building, like heating, cooling, lighting and equipment, and also to architectural strategies used in the project stage, as well as the building's profile and energy consumption. That meets data from CBCS (Conselho Brasileiro De Construção Sustentável) [12], which show that about 50% of the energy consumption in these buildings comes from air conditioning systems. Buildings with large glazed areas are established as a style in contemporary corporative architecture [2, 13-16], a trend that is growing in Brazil in the last few years. However, in the Brazilian climatic context, such use may boost energy consumption. This way, the application of STPV technologies onto the buildings' glasses may be a strategy in search for better energy performance. Kapsis et al. [17] have presented, in their study, the impact of the application of STPV over lighting performance on façades of commercial buildings, adopting a concept of façade as divided into 3 sections. The lower section, with a height of 0.8 m from the ground (working plan), was defined as an opaque area, due to its little contribution to daylight. On the middle section, 1 meter higher from the opaque area, PV technologies with thin film have been applied, whereas in the upper section, silicon PV cells have been integrated, aiming to increase the reach of daylighting in the room, while protecting occupants from direct solar radiation and glare. Results have indicated that an STPV system with 30% visible transmittance, integrated to an external layer of insulated low-e glass, is able to provide enough daylight all year long, in Toronto.

In China, Sun et al. [18] have developed a model to assess the performance of an office with STPV application in five of the country's climatic conditions. Investigation has been carried out through computer simulation, with software EnergyPlus for energetic evaluations and radiance to evaluate daylighting performance in different window configurations. They concluded that, compared to double conventional glass, applying STPV may result in significant saving of energy, if the building has WWR $\geq$ 45% (window-wall ratio). Such configuration may result in up to 73% energy savings, and also provides better daylighting performance than conventional double glass, as it effectively reduces the possibility of glare. Rodrigues [19] studied the influence of STPV in glazed areas of commercial buildings in different climatic contexts in Brazil. The author verified, through a computer simulation with EnergyPlus, that, depending on the Brazilian region, STPV systems may contribute to increasing or decreasing consumption for artificial air conditioning. In Belo Horizonte (MG) and Florianópolis (SC), consumption was 3% and 8% higher, while in Vitória (ES) and Fortaleza (CE), there was a reduction of 1%. However, according to the author, the generation of photovoltaic power compensated for the increase in energy consumption. Didoné [4], in her study, presents results of lighting and energy performances in office buildings with STPV in the cities of Florianópolis and Fortaleza, in Brazil. Simulations were made with software EnergyPlus and Daysim. BIPV has shown to be a promising option to replace traditional materials. According to the author, it is only possible to achieve 500-lux illuminance near a window with WWR > 50%, with maximum depth of 3.5 m, in both cities. With WWR < 50%, distances get shorter. From the studies presented herein, it is possible to notice that glazed areas on façades have been showing up as essential elements in the search for balance between quality of daylighting and energy consumption in the building. This way, application of STPV may represent an additional contribution, through the generation of electric power.

2.1 Daylighting and Thermoenergetic Performances in a Computer Simulation

Computer simulation can be an important tool to aid designers in the project process, to obtain better lighting and thermoenergetic performances in buildings. The software EnergyPlus stands out among several simulation programs, as one of the most reliable and most used tools in the world for achieving energy efficiency in new or previously built buildings, operating according to the ASHRAE 140 [20]. In addition to thermoenergetic analysis, EnergyPlus offers different options of configurations to estimate the production of photovoltaic power: Simple, Equivalent One-Diode and Sandia. The choice of method will determine the mathematic models used to estimate energy production [21], providing project decisions that are more connected to reality. To develop this research, the method used was the Simple one, which only needs a fixed value as input data for the module's efficiency and does not require detailing matrices of specific modules. In what concerns the evaluation of the building's daylighting performance, it is imperative to evaluate availability of daylight, visual comfort, and their effects over the building's thermal load, in an integrated way [22]. In this sense, EnergyPlus software can be used to analyze daylighting, although many works have proven its limitations to assess lighting performance. A study by Ramos and Ghisi [23] confirms that EnergyPlus overestimates the amount of daylighting indoor, as well as consumption of electric power. So, one of the strategies to overcome the software's restrictions is integrated computer simulation that associates energy analysis made with EnergyPlus and daylighting analysis made with other specific software. Works like the ones by Didoné [24], Chi et al. [25], Lavin and Fiorito [26] and Moura et al. [27] are examples of research that use integrated computer simulations as a method of analysis. Thereby, software Rhinoceros with the DIVA-for-Rhino plugin, is one of the options that can be used to carry out daylighting simulations, for it allows to evaluate daylighting through climate-based data (CBDM—Climate-Based Daylight Modelling).

2.2 Photovoltaic Technologies in Buildings

Solar photovoltaic technology is a renewable source that generates power in a decentralized way, which is advantageous compared to other sources, for it decreases losses along the distribution process, since it can be directly applied to the consumption point. The integration of this system to buildings is considered easy and can be made by installing panels covering the building or replacing construction elements. Both presentations of BAPV (Building-Applied Photovoltaic) or BIPV (Building-Integrated Photovoltaic) systems are an efficient and sustainable solution to generate electric power in urban centers. The availability of solar radiation in Brazil is considered as a positive aspect for choosing photovoltaic solar technology. The country is privileged in what concerns solar energy, as it has one of the best levels of solar radiation in the world (1,534-2,264 kWh/m^2/year, on horizontal surface), as represented in Fig. 1.

In an analysis of the energy potential of the countries that invest the most in solar PV energy, like China (949-2,118 kWh/m^2/year), USA (730-2,191 kWh/m^2/year), Japan (1,022-1,607 kWh/m^2/year),

Fig. 1 Global horizontal solar radiation, in average annual values for daily totals in kWh/m^2/day.
Source: Ref. [28].

Germany (949-1,241 kWh/m^2/year) and Italy (1,022-1,899 kWh/m^2/year), it is possible to notice that in Brazil solar radiation is higher and more uniform in its distribution, compared to the leaders of the PV market. In addition to that, solar photovoltaic energy has grown 979% in the internal energy offer in Brazil between 2016 and 2017, which shows its importance in the country [29]. From an architecture point of view, alternatives for integration of photovoltaic elements to buildings present excellent esthetical value. In such sense, the modules may offer a possibility of use not only of energy generation, but also for esthetical reasons, while generation of electricity becomes a benefit and/or a consequence. Garviria et al. [30] have analyzed the potential of energy generation through photovoltaic systems, on façades in buildings, considering urban configurations and their influences over the availability of solar radiation. For these authors, the use of the buildings' façades to generate electric power has proven to be beneficial. Didoné et al. [11] analyzed the potential of office buildings in Brazil to become ZEB (Zero Energy Buildings), by decreasing consumption and using photovoltaic solar energy. The authors have assessed the use of PV technology in different parts of the building's envelopment and concluded that applying STPV onto glasses would provide 21% of power for the city of Florianópolis, SC, Brazil. Among the PV technologies available in the market, studies point that, for office buildings, STPV systems with thin film are more appropriate than the ones made with crystalline silicon, regarding aesthetics and their uniform appearance [31, 32]. Also, they are more accepted, due to their uniform aspect both inside and outside buildings, even when they are darker.

The photovoltaic thin film technology offers several new application options. They are created using semi-transparent materials like glass for the encapsulation of cells and building the module [33]. In addition to that, they may be built from simple, double, or triple glass, with PV cells in the back of the front panel or in the front of the back panel [34]. So, considering the need for further studies about the influence of semi-transparent photovoltaic technologies, this work presents the analysis of the impact of STPV system integrated to glazed façades of a room in an office building, in what concerns the use of daylighting and thermoenergetic performance.

3. Method and Materials

The research method used in this study was integrated computer simulation, by modelling with software SketchUp Make 17, with Euclid plugin version 0.9.3 and simulating with software Energy Plus 8.7.0, to assess thermoenergetic performance and generation of photovoltaic energy. Meanwhile, daylighting simulations were carried out with software Rhinoceros with DIVA-for-Rhino plugin. The stages of this method were divided according to Fig. 2. They are: (i) literature review; (ii) definition of the case study; (iii) modelling and configuration of the base case and reference cases; (iv) definition of the type of

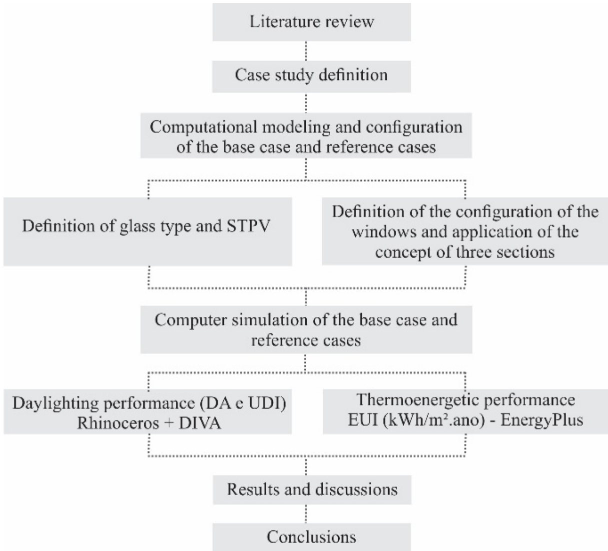


Fig. 2 Flowchart of the research stages.
Source: the authors (2020).

glass and STPV, as well as the configuration of glasses and the division of the façade according to the three-section conception; (v) computer simulation of the base case, without photovoltaic generation, and reference cases, with STPV integrated to glaze; (vi) analysis of the results of daylighting and thermoenergetic performances and photovoltaic generation in the reference cases; vii) result and discussions; (viii) conclusions.

3.1 Case Study

An office room located in the middle floor of a 3-floor horizontal building with North-South orientation located in the city of Pelotas, RS, in southern Brazil (31°46′19″ S, 52°20′33″ W) was defined as object of this study. The room presents an area of 411.59 m^2, according to Fig. 3a. From this model (Base Case), five reference cases were defined, with different configurations of STPV applied to the façade's glazed area (Fig. 3).

3.2 Computational Configuration of the Base Case and Reference Cases

In order to obtain results of daylighting and thermoenergetic performance, the concept adopted was the one of the three-section façade with application of STPV modules with different transparency percentages and their variation that combines STPV and low-e glass. Those were compared to Base Case, without photovoltaic generation. The concept of a façade divided in three sections has been used by Kapsis et al. [17], who defined a façade configuration divided into three different regions. To develop the method for this work, their conception was used in the definition of configurations of glazing sections and distribution of STPV. This way, we defined: a lower section of 0.6 m, an area with little contribution to daylighting, followed by a middle section of 1.2 m, a visualization area, and an upper section, also 1.2 m high, explored to potentialize the reach of daylight. The division of heights has been adjusted according to the dimensions of STPV modules, both measuring 1.2 × 0.6 m and depth of 6.8 mm. The configurations of the windows studied are presented in Fig. 3.

In the configuration of the Base Case, the three sections consist in double low-e glasses, without application of STPV. As for the configuration of Cases A, B and C, STPV was used in the three sections, with different transparencies available in the market: 10%, 20% and 40%, respectively. Cases D and E combined STPV and low-e glass. So, for Case D, STPV was applied with 10% transparency on the lower section, while middle and upper sections are composed of low-e glaze without STPV. As for Case E, modules STPV with 10% and 40% transparency were applied, respectively, onto the lower and upper sections, while the visualization area remained without STPV. The types of glass used in computer simulations are presented in Fig. 4.

The Base Case consists in one insulated glass, with its external part composed of low-e 6 mm glass, an air layer of 13 mm and its internal layer of colorless 3 mm glass (Fig. 4a). As for the cases with STPV application, they were composed of insulated glass, external part of low-e 6-mm glass, internal colorless 3 mm glass and a layer of photovoltaic cells encapsulated between the glass panels (Fig. 4b). To determine thermal and optical properties of the glasses used in the Base Case and in the reference cases (with STPV windows), this study referred the analysis data by Do et al. [35], who used information from the window library of the program WINDOW 7.3 [36]. Electric performance of the STPV selected was obtained from published data [37]. Table 1 presents the properties of the glasses used in the models. In the STPV cases, the three different transparencies were named Type a, Type b and Type c, as seen in Table 1.

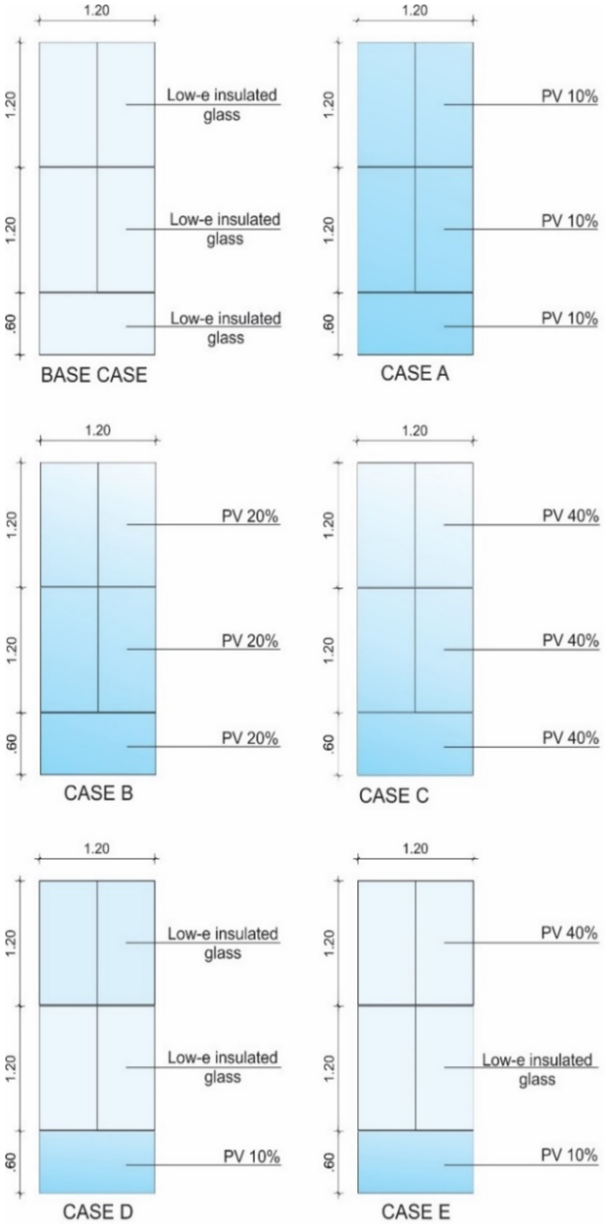


Fig. 3 Scheme indicating analysis models.
Source: the authors (2020).

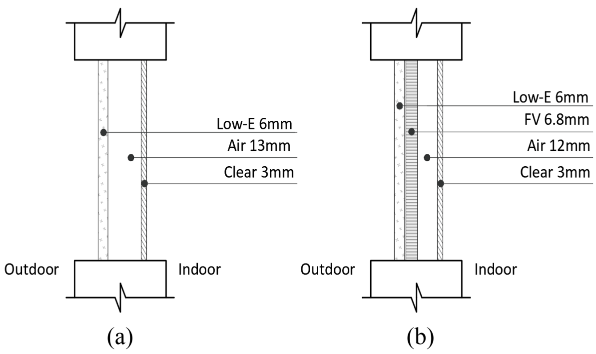


Fig. 4 Configurations of the windows studied.
Source: the authors (2020).

3.3 Computer Simulation of Lighting Performance

The office room was modeled in software SketchUp Make 17 and simulated in software Rhinoceros 6 with DIVA for Rhino plugin, version 4.1.0.12. Fig. 5 represents the tridimensional model. Simulations were made in ideal conditions, with no obstructions in the surroundings. Furniture was disregarded, in order to make it possible to extend results to other contexts.

Aiming to consider the location of the model analyzed, the climate file of the city of Pelotas, as developed by Leitzke et al. [38] was inserted. The city is located in Climate Group 5, according to INI-C—Normative Instruction by Inmetro [39]

Table 1 Thermal and optical properties of glasses.

Properties	Base case	Reference cases BIPV		
		Type a	Type b	Type c
Transparency (%)		10	20	40
Nominal power (W)		72	64	48
Efficiency (%)		10	8,89	6,67
Thickness (mm)	6.000	6.800	6.800	6.800
Solar transmittance	0.230	0.043	0.138	0.308
Solar reflectance (front)	0.370	0.119	0.212	0.106
Solar reflectance (rear)	0.550	0.449	0.413	0.268
Visible transmittance	0,580	0.101	0.203	0.403
Visible reflectance (front)	0.120	0.223	0.224	0.106
Visible reflectance (rear)	0.080	0.347	0.336	0.235
Emissivity (front)	0.840	0.840	0.840	0.840
Emissivity (rear)	0.220	0.450	0.540	0.730
Conductivity (W/m·K)	1.000			

Source: Refs. [35, 37, 40].

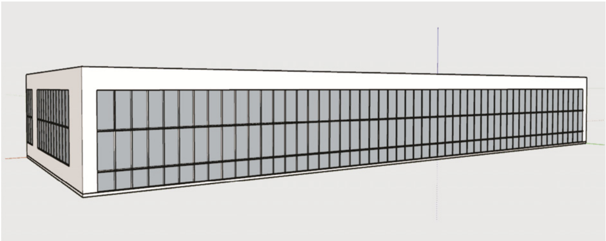


Fig. 5 Tridimensional model simulated in software Rhinoceros with DIVA plugin.
Source: the authors (2020).

Table 2 Reflectance and transmittance of materials.

Components	Component characteristics	Reflectance (%)
Exterior wall	White paint	75
Interior wall	White paint	75
Floor	Medium gray carpet	20
Door	Wood	50
Façade structure	Aluminum	65
Ceiling	Plaster with white paint	75
Components	**Component characteristics**	**Transmissivity (%)**
Glass	Low-e 6mm	58
Glass PV a	Transparency of 10%	10.1
Glass PV b	Transparency of 20%	20.3
Glass PV c	Transparency of 40%	40.3

Source: Refs. [37, 41]

(31°46′19″ S, 52°20′33″ W), and as humid subtropical climate according to the Köppen-Geiger classification. To allow daylighting analysis, light sensors were distributed in the office room, at a height of 0.75 m from the ground, which is the working plan indicated by NBR 15215-4 [42], and 2 m away from each other. Materials were configured according to Table 2.

To assess the dynamics of daylighting performance, analysis was made with (i) DA (Daylight Autonomy) that represents the percentage of hours of occupation during the year in which a minimum level of illuminance can be maintained with daylighting; (ii) UDI (Useful Daylight Illuminance) that corresponds to the percentual of hours of occupation in which illuminance values considered useful are achieved in the working plan. The daylighting system was configured according to orientations found in regulation NBR 8995-1 [43] which specifies illumination conditions for indoor workplaces and adopts the illuminance level of 500 lux as a standard for DA simulations. In what concerns UDI evaluations, the range of values went from 300 to 3,000 lux, considered by Mardaljevic [44] as autonomous UDI. At this range, it is likely that daylight is not enough, making electric lighting necessary. UDI evaluations allow to analyze useful illumination levels and also to consider the possibility of glare. That is one of the main differences from the DA analysis.

3.4 Computer Simulation of Thermoenergetic Performance

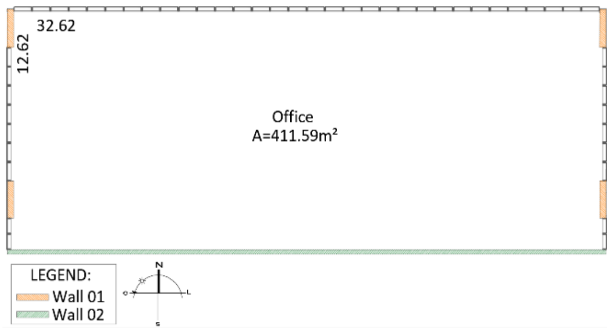
Thermoenergetic performance simulations were modelled with software SketchUp Make 17 and simulated with EnergyPlus version 8.7.0.

3.4.1 Geometry and Definition of Thermal Zones

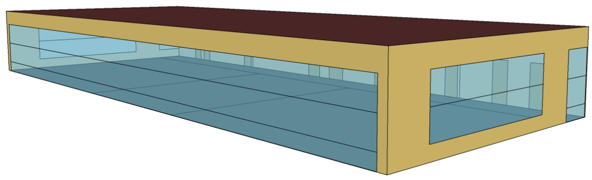
The office room was modelled with a thermal zone measuring 12.62 m × 32.62 m and clear ceiling height of 3.85 m, according to schematic plan and tridimensional model presented in Figs. 6a and 6b. Air infiltration was configured in simulations with 0.6 air exchange/hour, according to orientations by CIBSE [45].

3.4.2 Construction Characteristics

The office room was built with the light steel frame construction system. It is important to stress that all

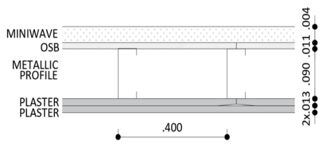
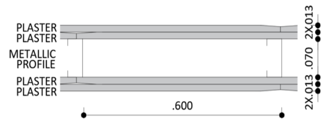


(a)



(b)

Fig. 6 (a) Schematic plan with solar orientation; (b) tridimensional model of Base Case—SketchUp and Euclid plugin.
Source: the authors (2020).

Configuration type	Material	Thicknes s (m)
WALL 01: external walls		
	Miniwave	0.004
	OBS	0.011
	Light steel bar + air cavity	0.090
	Gesso	0.013
	Gesso	0.013
WALL 02: internal wall	Gypson board	0.013
	Gypson board	0.013
	Light steel bar + air cavity	0.090
	Gypson board	0.013
	Gypson board	0.013

Board 1 Configuration of the model's walls.
Source: the authors, based on the architectural project (2020).

the walls have, between their panel faces, rock wool isolation with around 0.05 m tick. Internal and external walls of the study model are presented on Board 1.

Characteristics of other construction elements, as well as their thermal proprieties, are presented in Table 3.

All the walls in Base Case are coated of aluminum panel, and the openings have low-e 6 mm glass + air layer with 13 mm and 3 mm simple glass (6 + 13 + 3). Properties of the glasses were presented in Table 2.

3.4.3 Configuration of the Daylighting System, Occupation Standards, Equipment and Artificial Air Conditioning

Table 4 presents values of internal loads and artificial air conditioning used in the computer simulation. These values are based on the electric lighting project and on data recommended by INI-C. This instruction defines a new methodology to classify the level of energy efficiency of commercial buildings in Brazil, aiming to promote a reduction of consumption of electric power in these buildings [39].

A dimmable lighting system was configured to integrate the use of daylighting and electric lighting and thus obtain more precise data about consumption for illumination. To make it possible, sensors were added and configured to be activated when minimum illuminance of 500 lux prescribed by NBR 8995-1 [43] for offices is not achieved. They were set in the central axis of the room in the building model. Energy analysis regarding illumination was carried out with software Energy Plus 8.

Table 3 Construction parameters of the models.

	Material	t (m)	λ (W/m·K)	ρ (kg/m^3)	c (J/kg·K)	U (W/m^2·K)
Walls	CAP (composite aluminum panel)	0.004	230	2,700	880	0.637
	Mini-wave	0.004	230	2,700	880	0.603
	OBS (oriented strand board)	0.011	0.17	650	2,300	0.641
	Air	External walls = 0.09 m and internal walls = 0.07 m				
	Rock wool	0.050	0.045	100	750	0.644
	Gypson board	0.013	0.350	750	840	0.609
Roof	Aluminum roof tile	0.004	230	2,700	880	
	Air					
	Concrete slab	0.100	1.75	2,200	1,000	1.719
	Glass wool	0.100	0.045	50	7,000	
	Gypson board	0.013	0.35	750	840	
Internal door	Plywood sheet	0.005	0.120	300	1,340	
	Air					
	Plywood sheet	0.005	0.120	300	1,340	
Windows	Aluminum frames					5.733
	Insulated glass			Table 2		
Floor	Carpet floor	0.005	0.07	200	400	
	Expanded polystyrene (EPS)	0.030	0.04	25	1.42	2.876
	Concrete slab	0.150	1.75	2,200	1,000	

Source: the authors and architectural project (2020).

Table 4 Characteristics of internal loads and air conditioning system.

Characteristics of internal loads		
Use	Characteristics	References
Electric lighting	8.10 W/m²	Lighting project
People	0.10 person/m²	INI-C
Equipments	9.70 W/m²	INI-C
Air conditioning system features		
Type of equipment		VRF with air condensation
Capacity		≥ 70 kW
Classification		Multi-split VRF
COP for cooling		3.33
COP for heating		3.40
Setpoint (heating)		21°C
Setpoint (cooling)		24°C

Source: Electric Lighting Project, Energy Plus and Ref. [39].

4. Results and Discussions

In order to analyze results, we carried out a parametric study in which configurations of glasses were varied, through inserting STPV with several percentages of transparency on different sections of the façade: STPV with 10% transparency (Case A); STPV with 20% transparency (Case B); STPV with 40% transparency (Case C); STPV with 10% transparency on the lower section and low-e glass in the other sections (Case D); STPV with 10% transparency integrated to the lower section, visualization area with low-e glass without photovoltaic generation and natural light area with application of STPV with 40% transparency (Case E). Results were compared to the Base Case without photovoltaic generation. This way, this chapter presents the evaluations of daylighting performance, photovoltaic generation, and energy performance of the building.

4.1 Daylighting Performance

Results of daylighting simulations in software Rhinoceros 6 with DIVA plugin are presented on a chart of false colors, which allows to identify, through the requested metrics—in this case, 500-lux DA and 300-3,000 lux UDI—illuminance levels regarding the building's occupation hours. This way, the use of daylighting was assessed in different configurations of windows with integrated STPV. Daylighting performance evaluations allowed to observe that applying STPV reduced the illuminance inside the office room in every scenario analyzed (Figs. 7 and 8). In what concerns only the use of daylighting, the Base Case, without STPV, has stood out, with 500-lux DA in 50% of the occupation hours and 300-3,000-lux UDI in 60.27% of the time occupied, and it was higher in the plan periphery in both analyses. However, UDI evaluations allowed observing the occurrence of glare in areas that are close to windows, as they are turned to solar orientations with direct solar radiation. The presence of illuminance higher than 3,000 lux was identified, since there was a reduction of the occupation hours within the value range analyzed, when DA and UDI results were compared. The application of STPV with lower percentages of transparency (cases A and B) in the three sections of the façade caused significant reduction of the access to daylight. Case A presented 4.7% DA and 12.38% UDI of occupied hours, making it necessary to use artificial lighting all along the working hours, for the occupants' visual comfort. A similar situation occurred in Case B, in which daylighting was only achieved in spots closer to windows, during a short period with 17.57% DA and 29.7% UDI. As the façade's transparency was increased, it was possible to observe higher reach of daylight, as well as occurrence of glare. However, the application of 40% transparency STPV (Case C) contributed to reducing the time with excessive illuminance, acting like a filter against direct solar radiation, compared to Base Case. Case C presented DA in 37.46% and UDI in 50.13% of the time of occupation. In addition to that, configurations that integrate STPV and low-e glass favored daylighting. In Case D, the application of STPV with 10% transparency did not interfere significantly in daylighting, compared to Base Case. Meanwhile, in Case E, in which the visualization area without STPV has shown to be advantageous from the

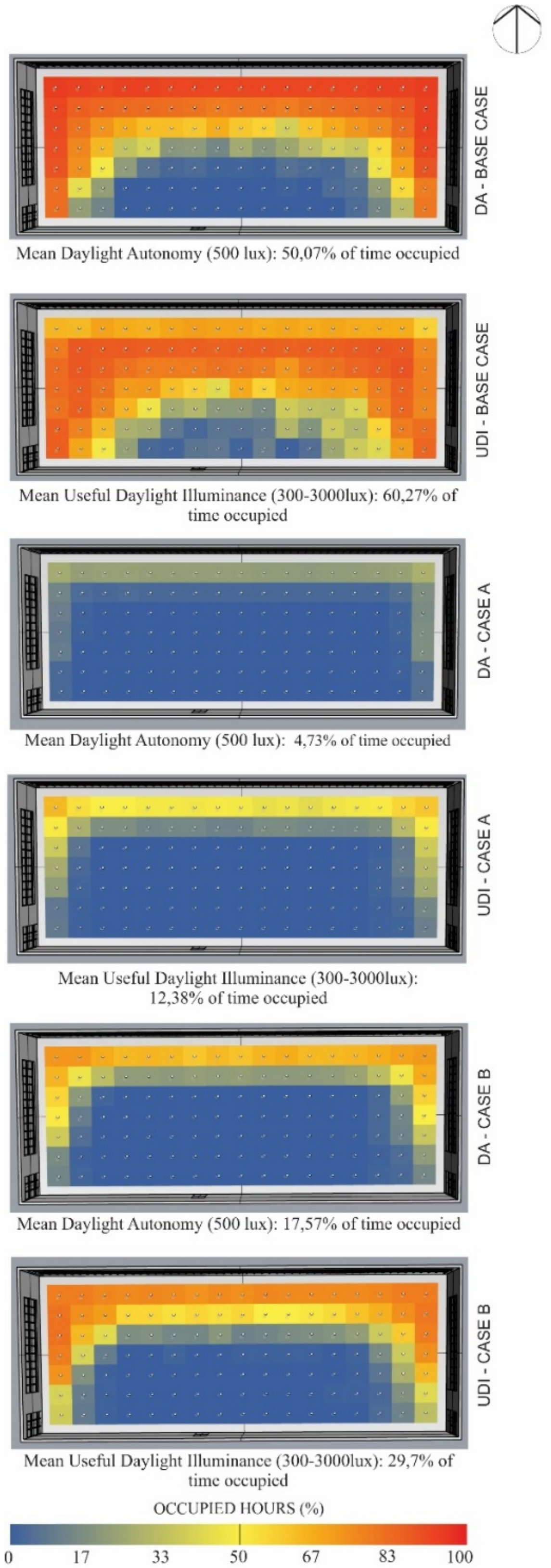


Fig. 7 Useful Daylight Illuminance analyses.
Source: the authors (2020).

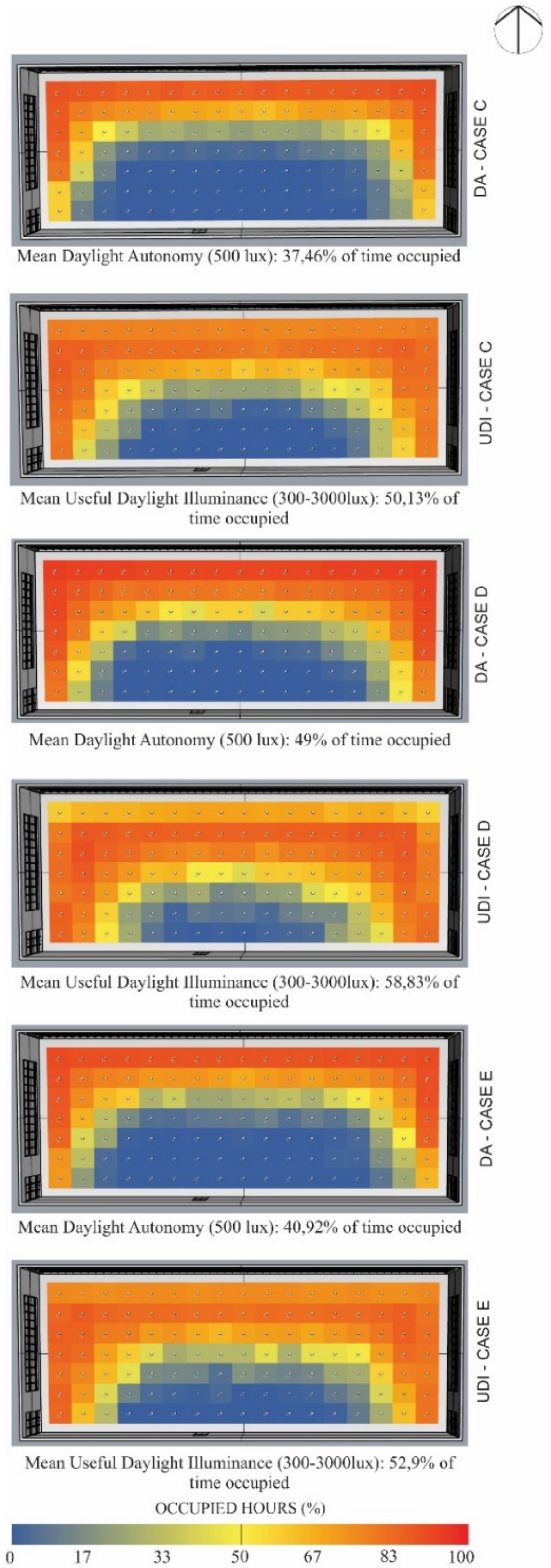


Fig. 8 Daylight Autonomy analyses.
Source: the authors (2020).

daylighting point of view, occurrence of glare was detected in areas close to windows. The excess of daylight must be seen with caution, as it may favor the occupants' interference in the building, through the use of solar control devices, and thus reduce the daylighting in the building. So, it can be stated that including STPV, although reducing daylighting, may improve the quality of daylighting with a balanced percentage of transparency of the module, minimize the effects of direct solar radiation and improve visual comfort for occupants.

4.2 Photovoltaic Generation

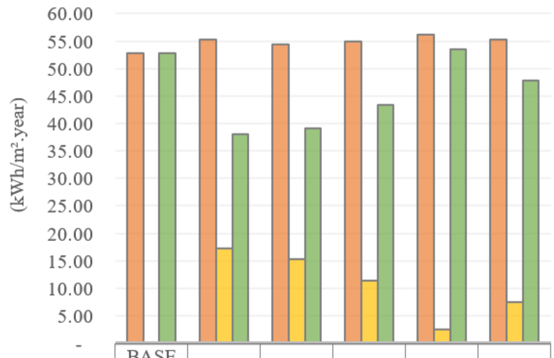
For the evaluation of photovoltaic generation, the same configurations of windows were studied. Fig. 9 shows that STPV modules with the lowest ratios of transparency presented the higher electric power generation, for they present greater cell efficiency. This way, Case A was responsible for 17.23 kWh/m^2·year of photovoltaic generation, followed by Case B with 15.32 kWh/m^2·year and by Case C with 11.49 kWh/m^2·year. As expected, in situations in which zones with photovoltaic and low-e were combined, there was a contribution for energy generation, however, it was lower. Case D presented 2.58 kWh/m^2/year and Case E, 7.46 kWh/m^2·year (Fig. 9).

Photovoltaic generation through glasses has shown potential to generate electric power for the climate studied.

4.3 Energy Performance of the Building

Results of photovoltaic generation were compared to those of energy consumption in the building, in order to profile its energy balance. Results showed that applying STPV onto the building's glasses has favored energy balance in almost every analyzed scenario, proving it to be an advantageous option to generate electric power through a renewable source.

The inclusion of STPV represented a 27.9% saving compared to the situation with the best energy balance. Case A presented 38.09 kWh/m^2·year, followed by



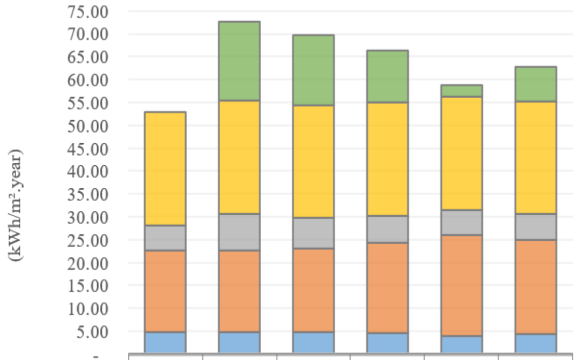
	BASE CASE	A	B	C	D	E
Total energy consumed	52.86	55.32	54.41	54.93	56.17	55.24
Total PV power generation	-	17.23	15.32	11.49	2.58	7.46
Total Energy Balance	52.86	38.09	39.10	43.44	53.60	47.78

Fig. 9 Chart on total consumption, PV energy generation and energy balance.

Source: the authors (2020).

Case B, that saved about 26%, and Case C, 17.8%, both compared to Base Case, that is responsible for 52.86 kWh/m^2·year of energy consumption. Among the configurations with STPV and low-e glass, Case E reduced consumption in 9.6% compared to Base Case. That did not happen with case D, which presented energy balance 1.4% higher than Base Case, although it may have generated 2.58 kWh/m^2·year of energy, due to consumption for cooling, originated from heat gains from the inclusion of the photovoltaic module. The positive energy balance found in this work meets the results by Didoné and Wagner [10], who verified that the use of STPV may reduce up to 43% of energy consumption in an office building located in the city of Florianópolis, SC, in the south of Brazil. The use of STPV also promoted an increase of the building's energy consumption in every approached hypothesis, with a variation from 2.94% to 6.25%, for southern Brazil climate. The main reason for this situation was the increase of thermal loads for cooling and artificial lighting, as seen in Fig. 10.

In what concerns the consumption for cooling in the building, there was an increase in cases with STPV with higher transparency (Case B—18.42 kWh/m^2·year and Case C—19.64 kWh/m^2·year), as well as in cases



	BASE CASE	A	B	C	D	E
Total PV power generation	-	17.23	15.32	11.49	2.58	7.46
Equipment	24.69	24.69	24.69	24.69	24.69	24.69
Lighting	5.54	8.02	6.56	5.91	5.54	5.62
Cooling	17.91	17.82	18.42	19.64	21.90	20.58
Heating	4.72	4.78	4.75	4.68	4.03	4.35

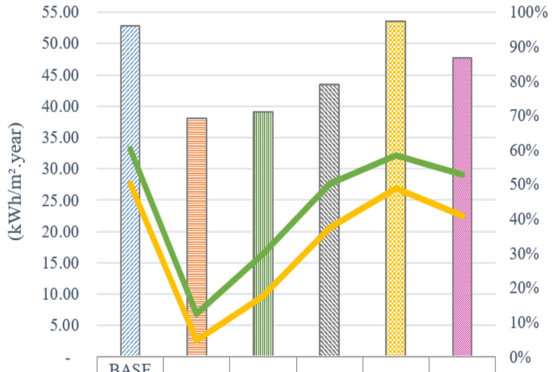
Fig. 10 Chart on energy consumption according to system.
Source: the authors (2020).

that combined photovoltaic modules and low-e glass: Case D with 21.90 kWh/m^2·year and Case E with 20.58 kWh/m^2·year, in comparison to Base Case, with thermal load for cooling the building of 17.91 kWh/m^2·year. The higher permeability of daylighting contributed to increasing the building's thermal load, combined with greater heat gain provided by STPV. Case A presented the lowest consumption for cooling the building, with 17.82 kWh/m^2·year, due to the lesser transparency of photovoltaic glaze, which allowed less daylighting inside the office room. The increase of consumption for cooling meets the research by Rodrigues [19], who analyzed the influence of STPV in different climatic conditions in Brazil. The author identified that consumption from air conditioning varied according to the different Brazilian climatic contexts, a situation that must be assessed in order to improve the use of solar photovoltaic energy. In addition to that, we can observe that Cases A and B have also had consumption for heat, which shows that although STPV contributes to greater internal heating, it may act as a filter against solar radiation, balancing heat gains in cases with less transparency. That can be noticed when comparing Case A, with more opacity, that boosted the consumption for heating but decreased for cooling, and Case B, that favored consumption for air conditioning in both situations. Regarding energy consumption for artificial lighting, the inclusion of STPV has boosted consumption in every context approached, and was higher in cases with more opacity, especially Case A, with increase for lighting 44.8% higher compared to Base Case, followed by Case B with 18.4%, and Case C with 6.68%. In Cases D and E that combined STPV and low-e glass, there was no variation in Case D and a non-significant increase (1.45%) in Case E, as those variations, with areas without STPV, have aided natural light to enter.

4.4 Daylighting Performance × Energy Performance

To assess daylighting and thermoenergetic performance, results were compared aiming to find the configuration with the best balance in both situations. This way, through simulations with daylighting, it was verified (Fig. 11) that Base Case showed more autonomy regarding daylighting, with DA of 50.07% and UDI of 60.27%. However, the configuration of STPV with the highest percentage of transparency applied to all glasses—40% (Case C)—stood out as the most advantageous one, as it presented the best balance point for access to daylight, quality of the illumination and energy balance of the building. This configuration presented a final energy balance 18% lower than Base Case, with DA of 37.46% and UDI of 50.13%.

Case A presented the best energy balance, 38.09 kWh/m^2·year, however, it reduced access to daylight inside the office room significantly, with 4.73% DA and 12.38% UDI. The same happened with Case B, which, besides being the second configuration with the best generation of photovoltaic energy, also boosted consumption for artificial lighting in 18.4% and for cooling in 2.85%. The integration of STPV in certain sections and low-e glass (Cases D and E) favored the access to daylight, on the other hand, it



	BASE CASE	A	B	C	D	E
Total Energy Balance	52.86	38.09	39.10	43.44	53.60	47.78
DA	50.07%	4.73%	17.57%	37.46%	49.00%	40.92%
UDI	60.27%	12.38%	29.70%	50.13%	58.38%	52.90%

Fig. 11 Chart on daylighting performance × thermoenergetic performance.

Source: the authors (2020).

caused considerable increase of consumption for cooling—22.3% (Case D) and 14.9% (Case E), and also showed problems with glare. This way, it is important to highlight that when we combine data of daylighting and thermoenergetic performances, results of this work show that in the city of Pelotas, RS, Brazil, the adequate adoption of STPV may provide more quality of daylighting and contribute to generating electric power, which makes it a viable system to improve the building's performance.

5. Conclusions

The work herein searched to evidence the influence of the insertion of STPV glaze in an office located in Southern Brazil. Results allowed to observe that the application of STPV is an advantageous alternative to climate studies, as it contributed to energy balance of the building, since it can provide from 9.6% (Case E) to 27.9% (Case A) saving in energy, depending on the STPV configuration adopted. In addition to that, it was verified that using STPV with adequate transparency percentage may balance energy in the building, as well as its daylighting performance. Although it reduces access to daylight, it may improve the quality of daylit and minimize the occurrence of problems related to glare. Thermoenergetic analyses have shown that, in the climatic context analyzed, application of STPV may favor the increase of consumption for cooling and electric lighting, however, savings in electric power through photovoltaic generation compensated for this increase caused by the system. Finally, it can be concluded, with this work, that the application of STPV presents great potential to improve the building's daylighting and thermoenergetic performances. However, there must be caution when choosing the adequate model, for it to balance the availability of daylight and the generation of photovoltaic electric energy. It is suggested that this study is broadened for other climatic contexts in Brazil, searching for more sustainable and energy-efficient buildings.

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